Workshop on CO_2 Mineralization for ENERGY RELEVANT MINERAL EXTRACTION

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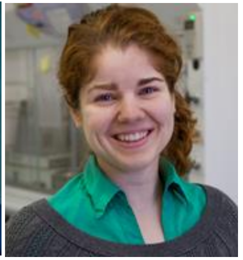
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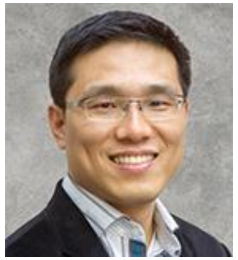
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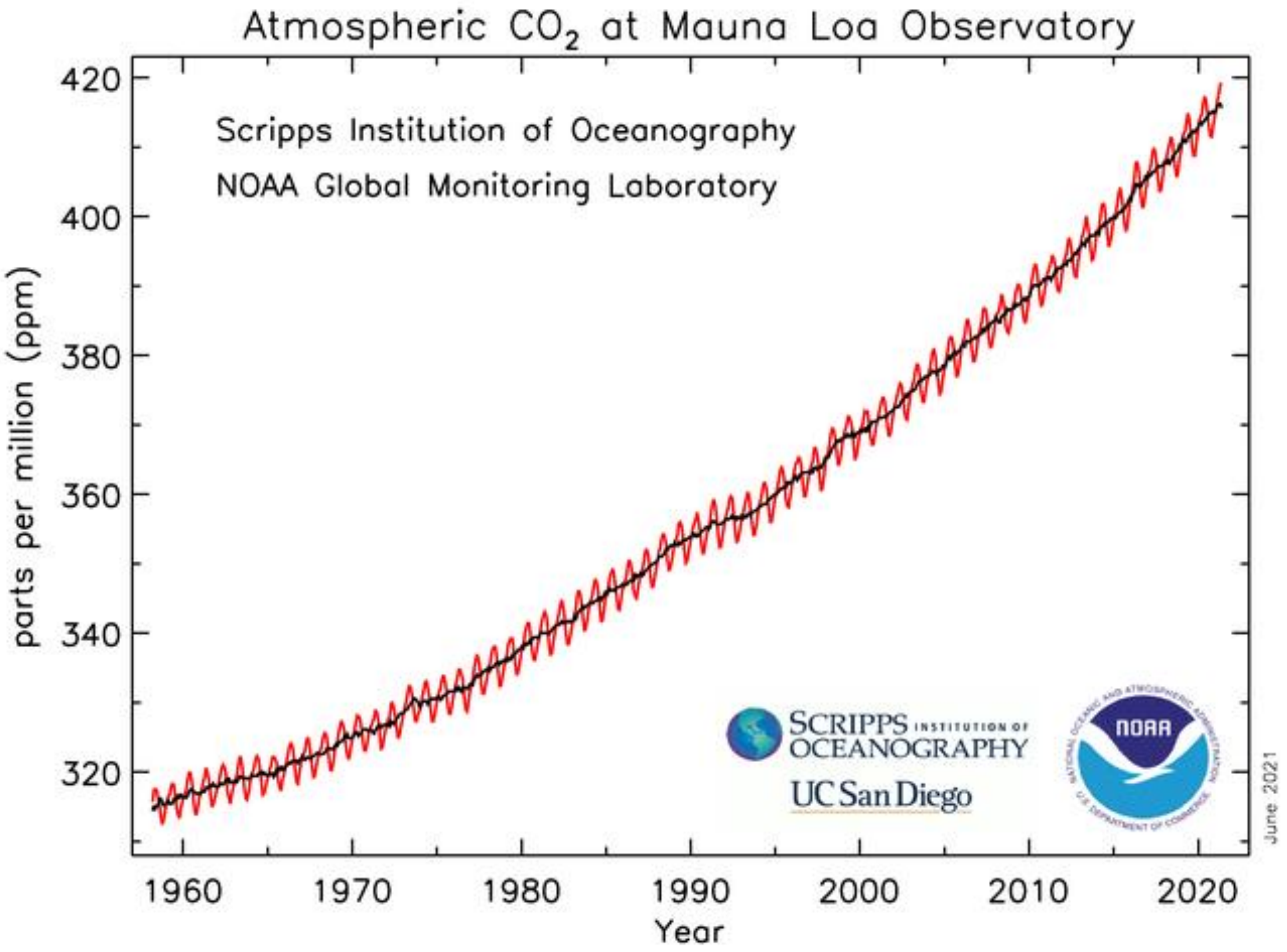
First Off

YOU'RE IN THE WRONG MEETING IF YOU:

- Don't think CO_2 is a problem
- Think atmospheric CO_2 removal is just green washing for the petrochemical industry
- Don't believe someone should make a profit getting rid of it
- Think our minerals for the energy transition are just going to miraculously appear.

If you're still here I don't have to tell you...



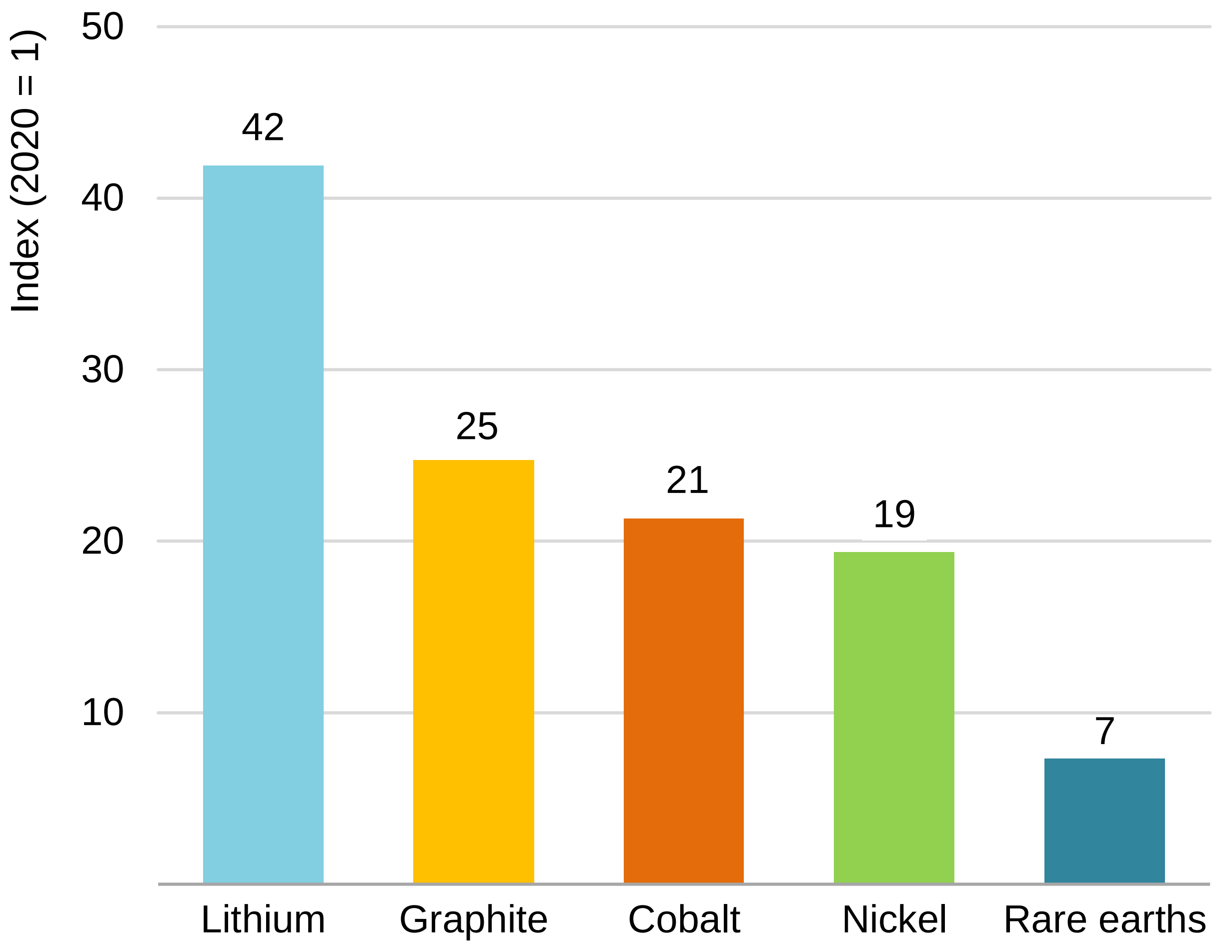
CHANGING WHAT'S POSSIBLE

But you may not have considered…

Sustainable Energy is Powered by Minerals

1	Aluminum	10	Manganese
2	Chromium	11	Molybdenum
3	Cobalt	12	Neodymium
4	Copper	13	Nickel
5	Graphite	14	Silver
6	Indium	15	Titanium
7	Iron	16	Vanadium
8	Lead	17	Zinc
9	Lithium		

Growth of selected minerals in the SDS, 2040 relative to 2020



Whose is interested in the Nexus between the two?

Investors

Mining companies

Academics

Carbon capture companies

A slew of government types from labs/Offices/Departments

Entrepreneurs

Visionaries and altruists

What is the Goal?

The use of CO_2 mineralization to improve the economics and environmental footprint of the extraction of energy relevant minerals

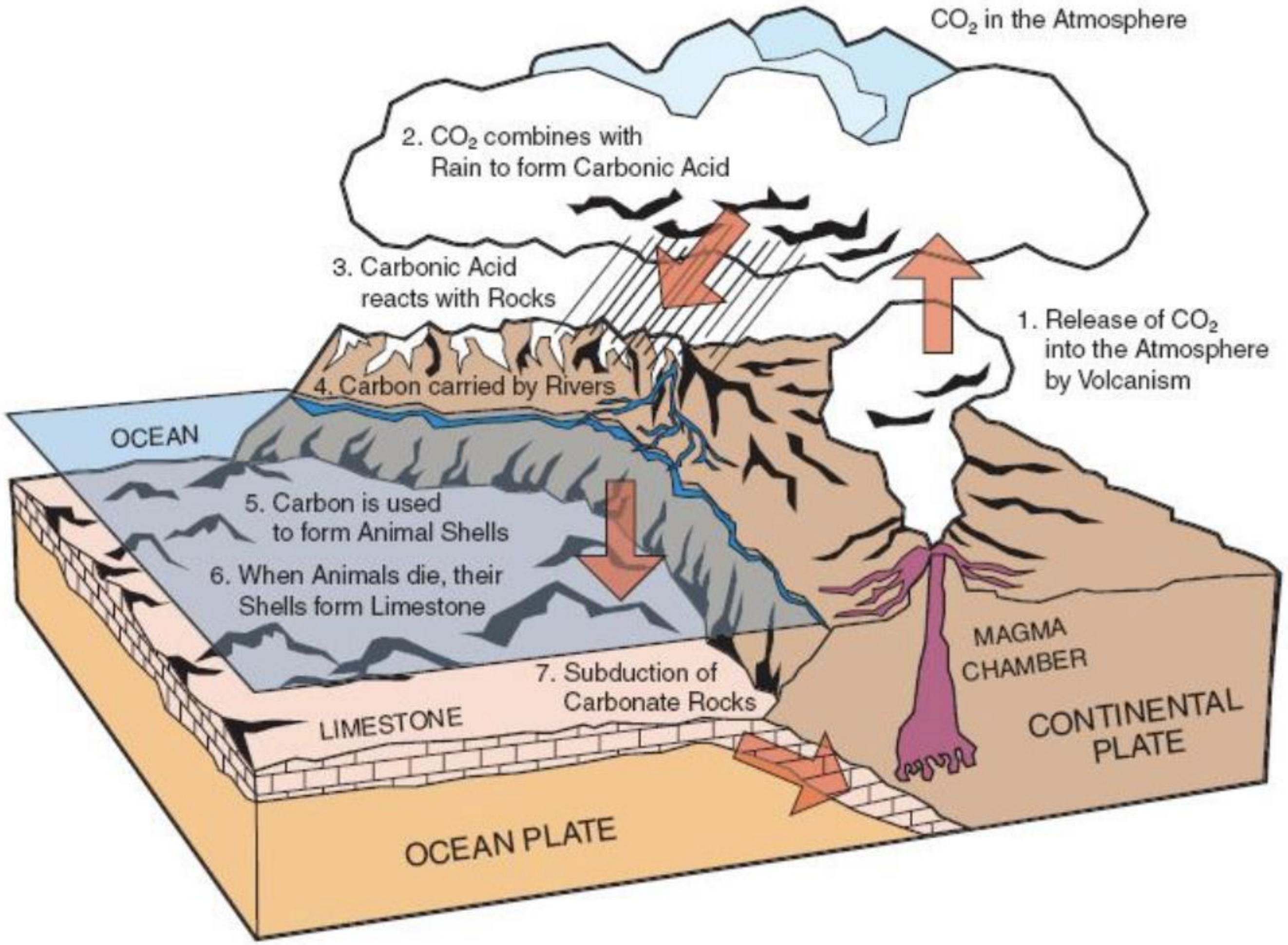
- **Economics**
  - Cost of sequestration << than carbon pricing
  - Income from carbon will impact mine economics
  - Expanding the breadth of viable deposits
- **Footprint**
  - **Permanent** CO_2 removal @ gigaton scale
  - Passivation of mine wastes
- **Concurrent technology developments of interest**
  - Improved downhole and waste tailings mineralization

It’s Pretty Simple Chemistry

wollastonite	$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$
olivine	$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$
pyroxenes	$CaMgSi_2O_6 + 2CO_2 \rightarrow CaMg(CO_3)_2 + 2SiO_2$
serpentine polytypes	$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$
brucite	$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$

- One just needs rock, CO_2, perhaps a little water…
- Thermodynamically favorable (-15 to -22 kcal/mol)
- Basically innocuous reaction products
- But…

But, in the wild this is a SLOW Process



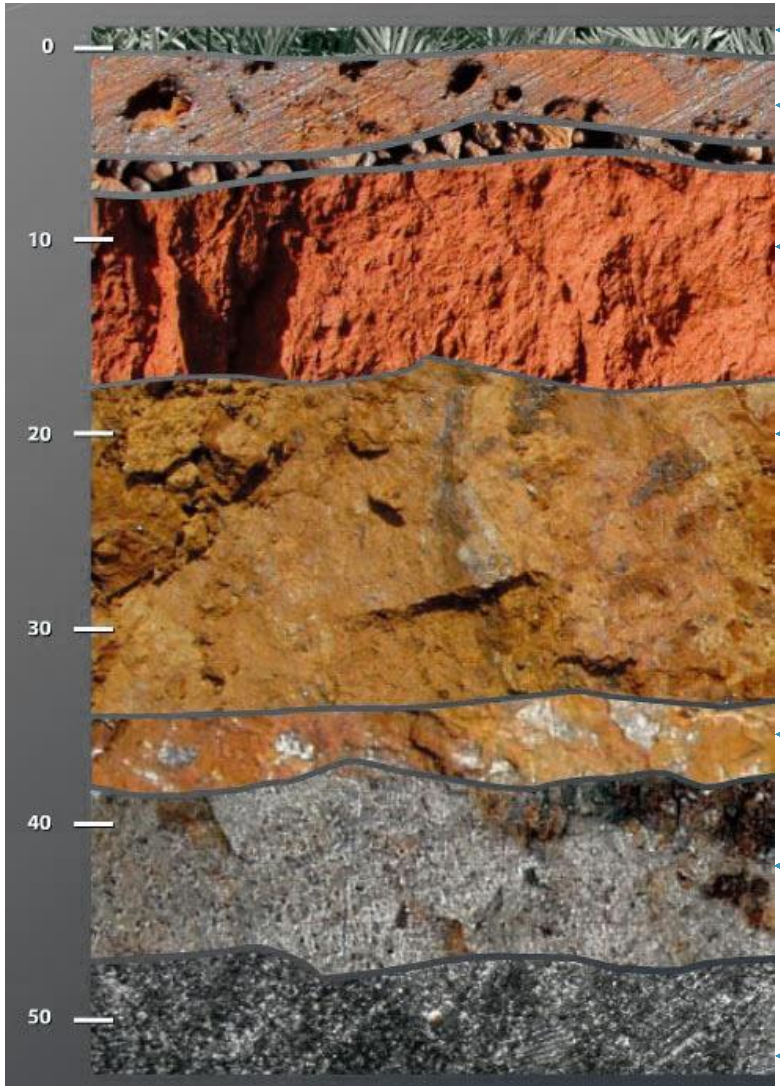
http://butane.chem.uiuc.edu/pshapley/Environmental/L29/2.html

Key to the erosion process that takes mountains into molehills!

Nature's way:

- Wind, rain, ice, freeze thawing, biology and seismic events all contribute to the process
- Removes about 1 gigaton of CO_2/yr
- It takes time – literal ***eons***

CO_2 Mineralization is a natural refining process



Vegetation

Iron Crust

Red Laterite

Yellow Laterite:
1.2 - 1.7% Ni
0.1 – 0.7% Co

Transition
1.2 – 2% Ni
0.1 – 0.25% Co

Saprolite
1.2 – 3% Ni
0.05 – 0.5% Co

Peridotite

Much of our current mining for nickel is from laterite ore bodies

- On a geological time scale Hydration and mineralization of CO_2 concentrates nickel in laterite
- As the reaction progresses manganese bicarbonate and silica leach away from surface
- Plants and microbes can produce acids and chelators that speed this weathering reaction to mine critical minerals while storing carbon

What are the targets for miners?

For: Ni, Cu, Co, Mn, Fe, Al, Mg, REE, PGM…

Make metal production carbon negative

More carbon sequestered than emitted downstream

Quantify and monetize fast

Done within the attention span of a corporate accountant – 90 days

Makes money at scale

Process cost \$15-20/tonne CO_2 mineralized

What's in scope?

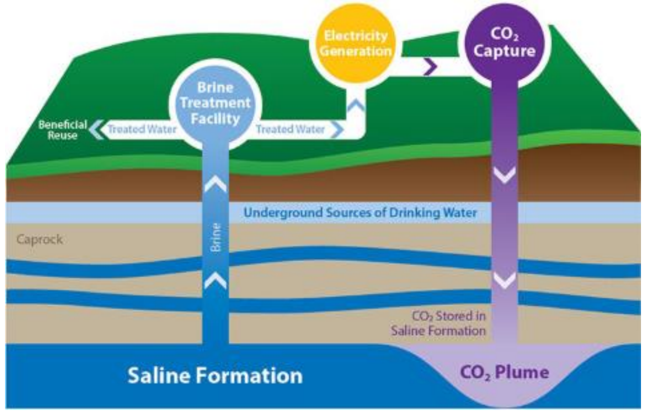
CO_2 Mineralization

In Situ Mineralization

- Subterranean storage methods
- Ore body pretreatment
- Acceleration of rock dissolution rates
    - Catalysis
    - Water & pressure management

Mineralization w/ Extraction

- Reactive extraction from ore
- Active mineralization in tailings
- Redeployment of tailings

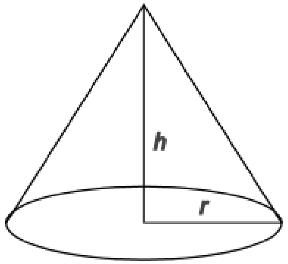


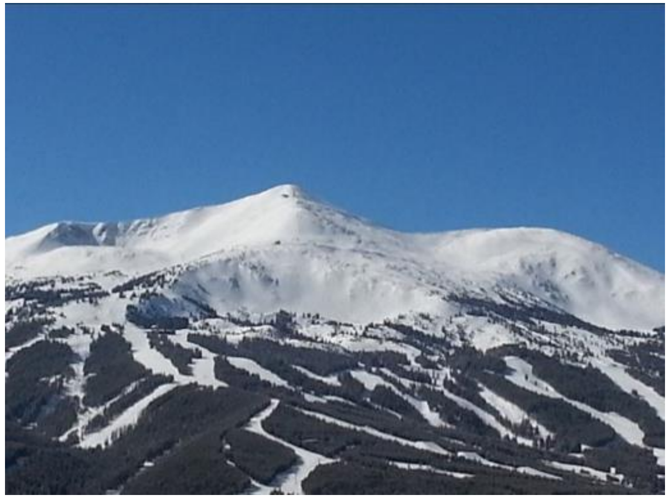
Common Ground

- Geology & petrology
- Identification and mapping
- Reaction chemistries
    - Thermochemical
    - Biochemical
- Metrology

Scale Scale Scale Scale SCALE

$$V = \pi r^2 \frac{h}{3}$$





Gigaton of CO_2 capture through mineralization

- **Needs** 1,600,000,000 tons of olivine:
  - Equivalent to *4X* ore produced by the worlds largest mine, or *4X* of everything taken from Lavender mine in Arizona
  - Leaving a 250,000,000 m^3 hole (think four NYC blocks of a solid mass higher than the Freedom Tower)
- **Results** in about
  - 2,500,000,000 tons of carbonate and silica
  - A cone of 1,000M high and 2,700M across (think Vail Mountain)

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Does the world have the infrastructure to support?

The global scale of extraction is almost Incomprehensible

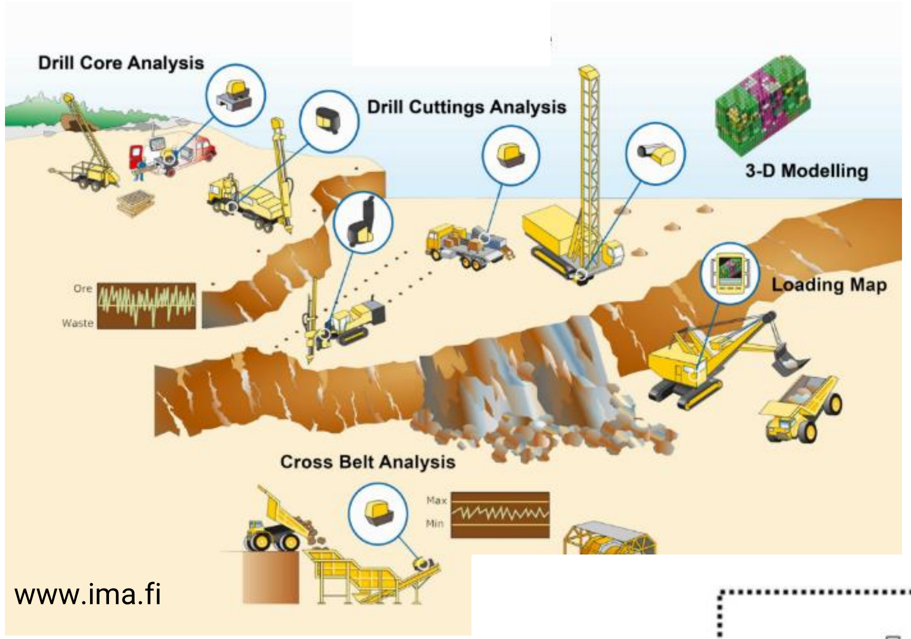
Yearly mineral production - 19 Billion tonnes
Coal/limestone/aggregate dominate

Yearly mining waste produced - 50 Billion tonnes
500,000,000 train car loads

Yearly oil/gas production - > 7.5 Billion tonnes
20,000 ultra large crude carriers

https://www.world-mining-data.info/wmd/downloads/PDF/WMD2020.pdf

For Mineral Extraction – 3 places to react with CO_2



During processing

- Comminution
- Floatation
- Extractive step

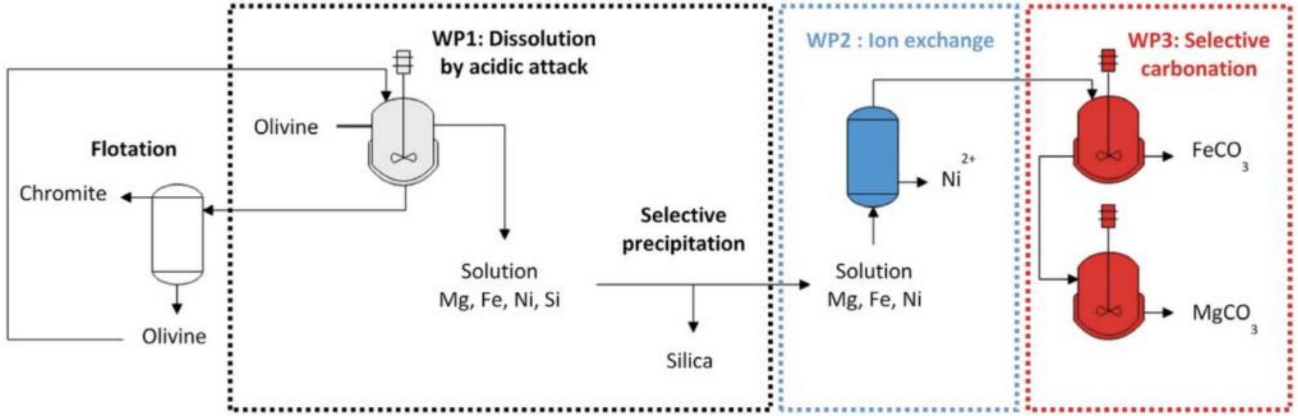


Figure 4

Schematic view of the process for CO_2 sequestration by indirect carbonation of olivine.

Pre-treatment

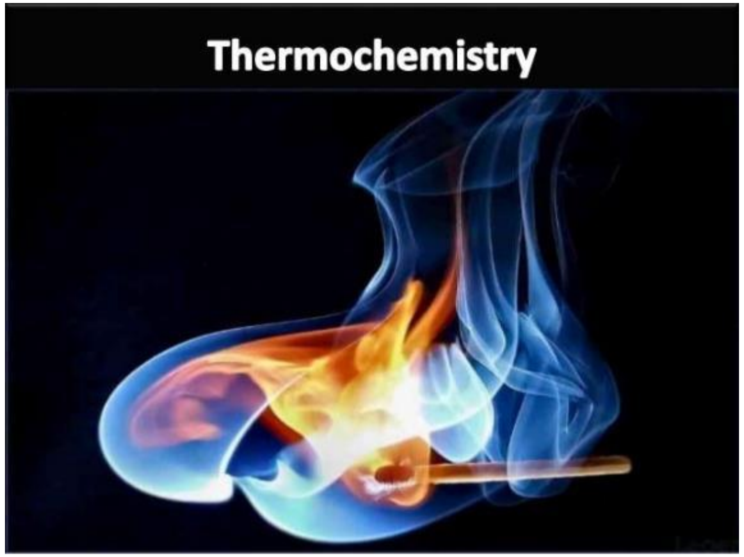
- Before extraction
- During extraction

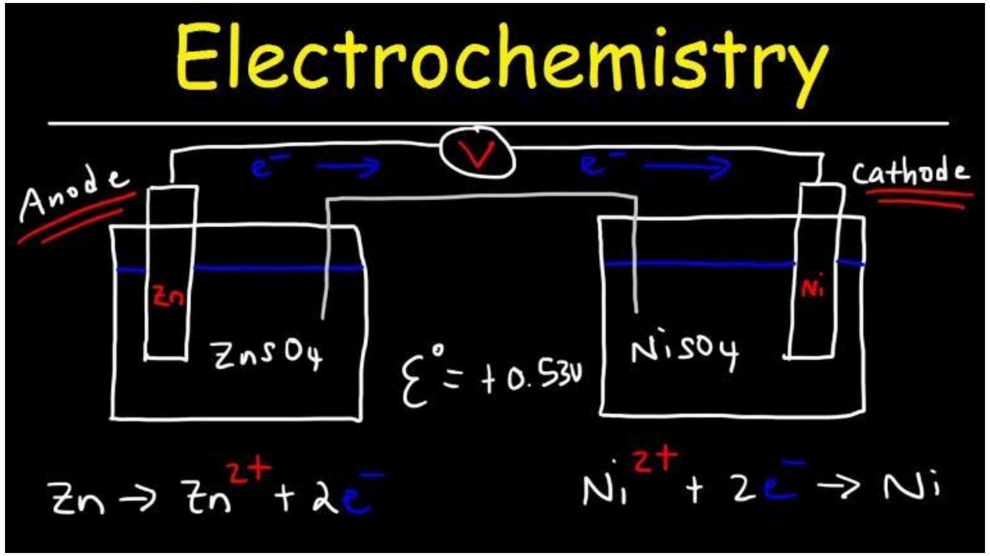
Post processing

- Before it the tailings pile
- Process residue
- Overburden

Turri et al https://doi.org/10.1515/gps-2019-0016

We see a blank slate of how to do





In Situ Mineralization

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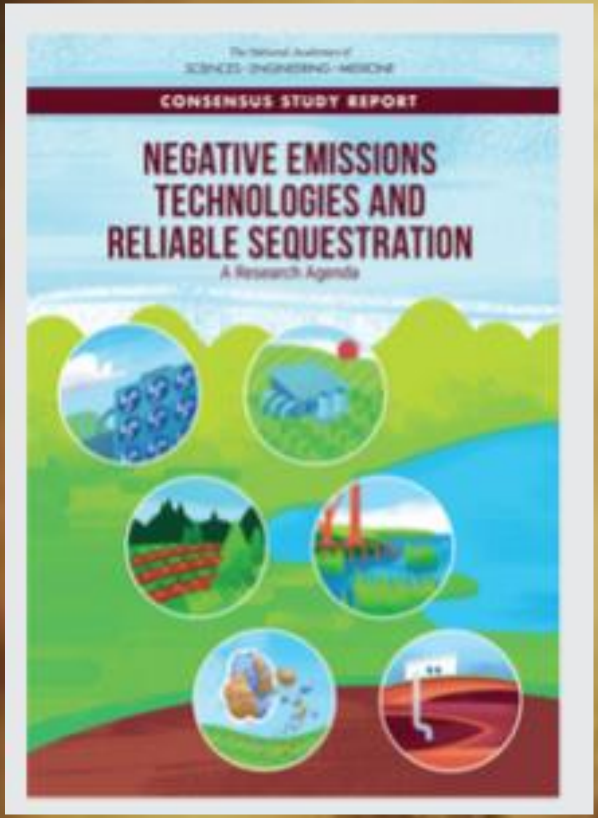
"Carbon mineralization is an emerging approach to remove carbon dioxide (CO_2) from the air and/or store it in the form of carbonate minerals such as calcite or magnesite."

"*In situ* storage . . . addresses many of the problems of *ex situ* solid storage but remains a largely speculative alternative."

Joseph King

July 13, 2021

National Academies of Sciences, Engineering, and Medicine 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

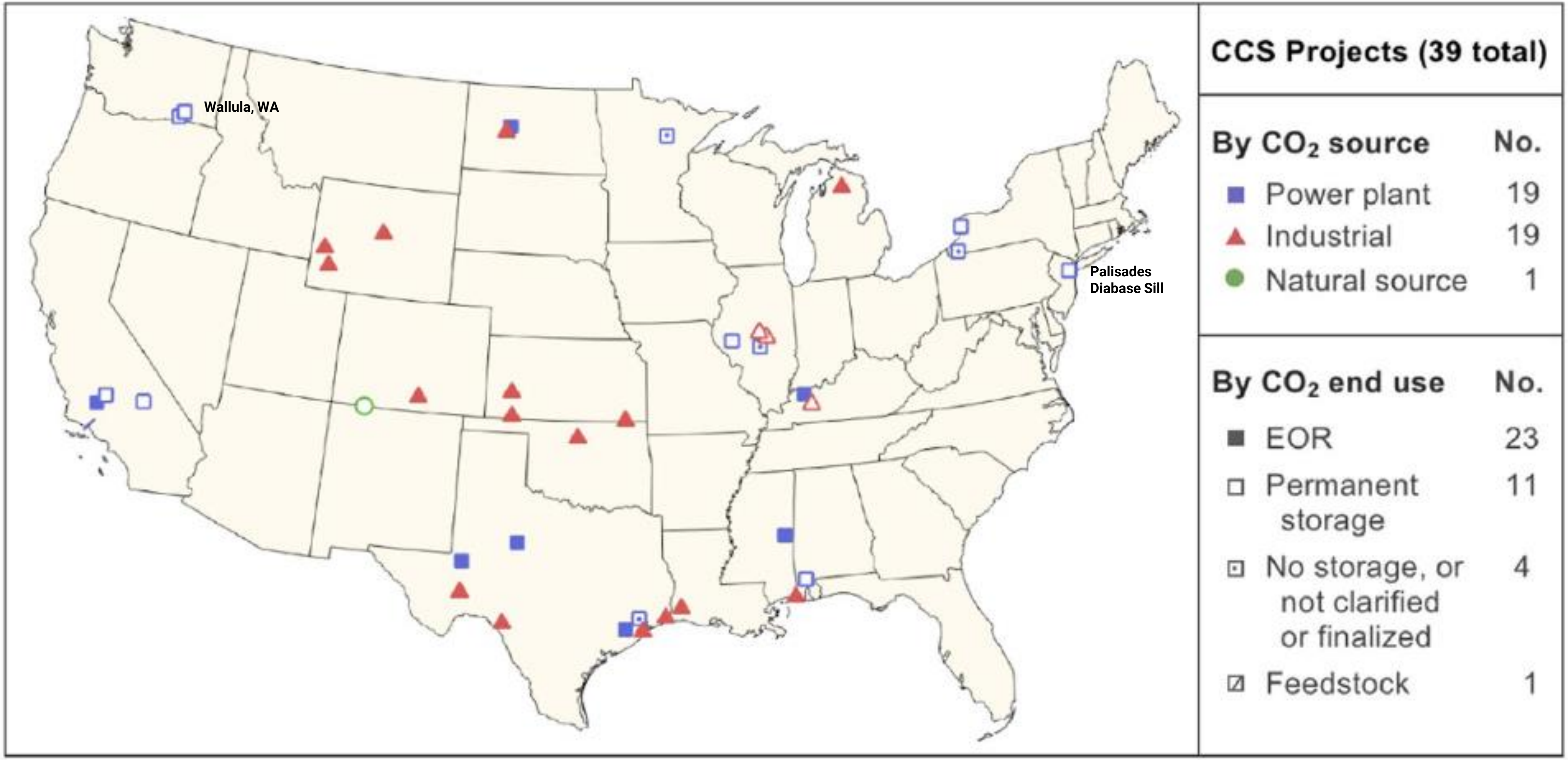


National Academies of Science, Engineering & Medicine 2019

Energy Futures Initiative December 2020

Princeton December 2020

Aggregate US CCS Projects



Across the 39, the applications and technologies employed are diverse and include demonstration, industrial, and power plant facilities. Twenty of 39 projects have been built; Ahmed Abdulla *et al* 2021 *Environ. Res. Lett.* **16** 014036

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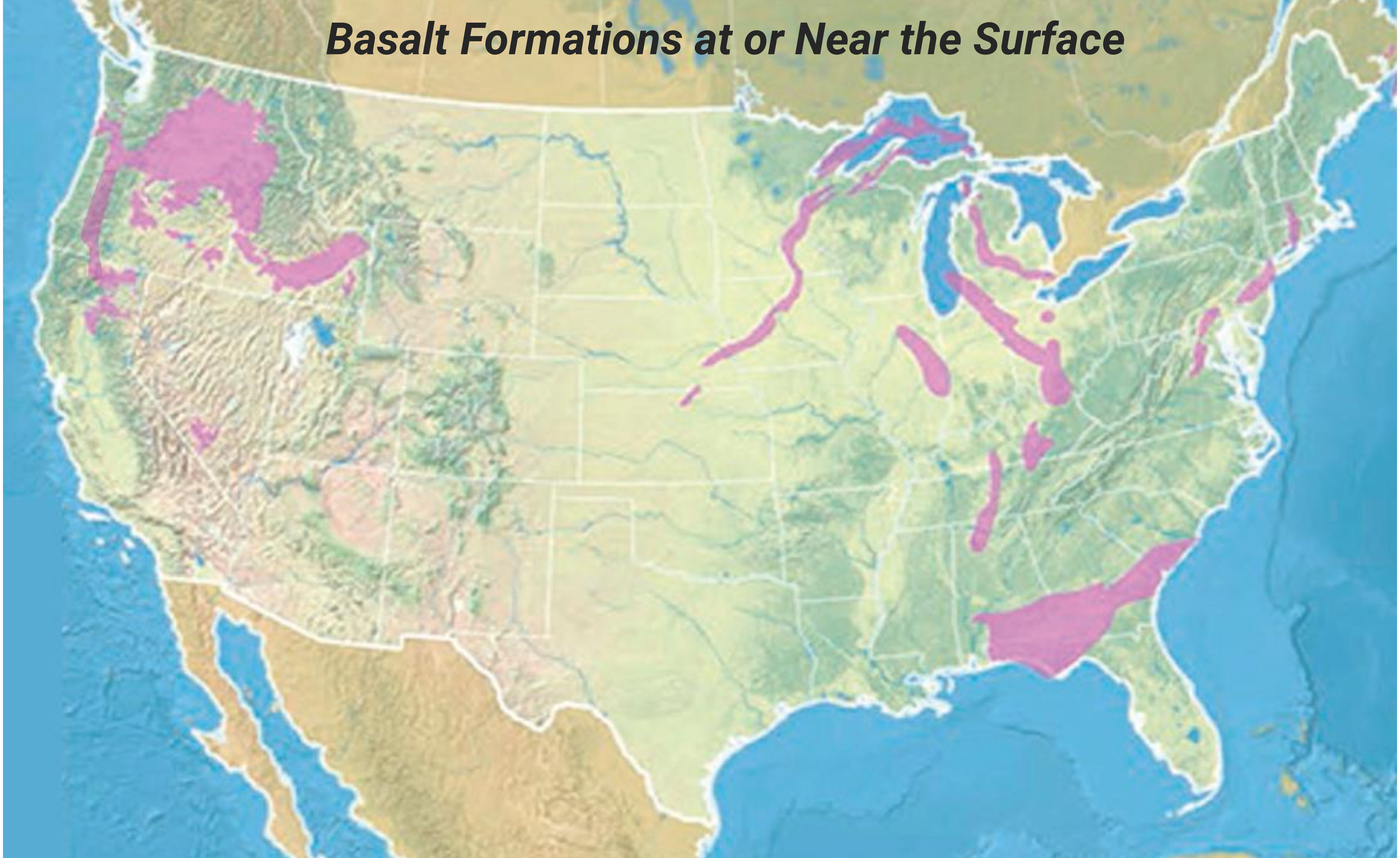
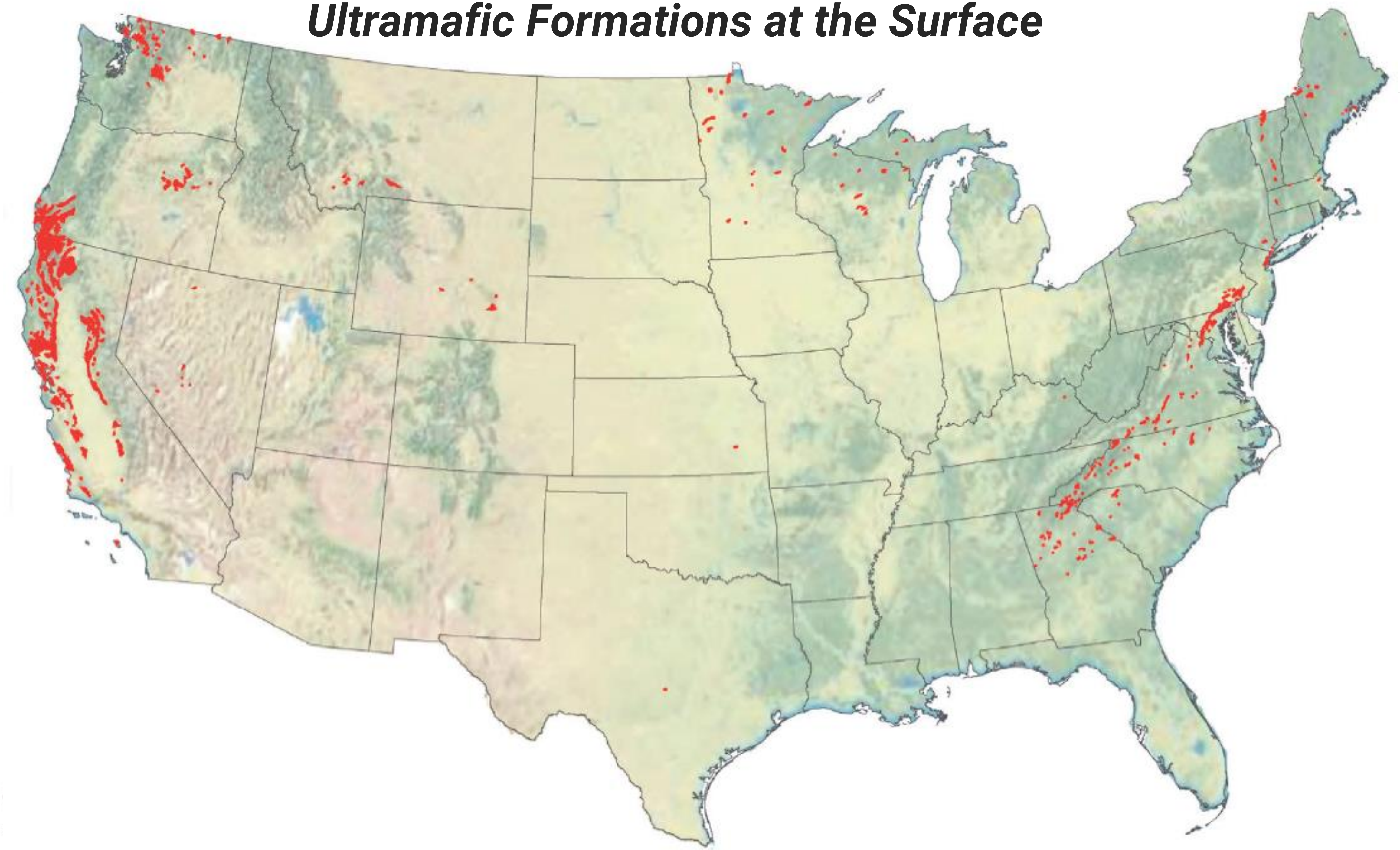
Basalt Formations at or Near the Surface



Ultramafic Formations at the Surface



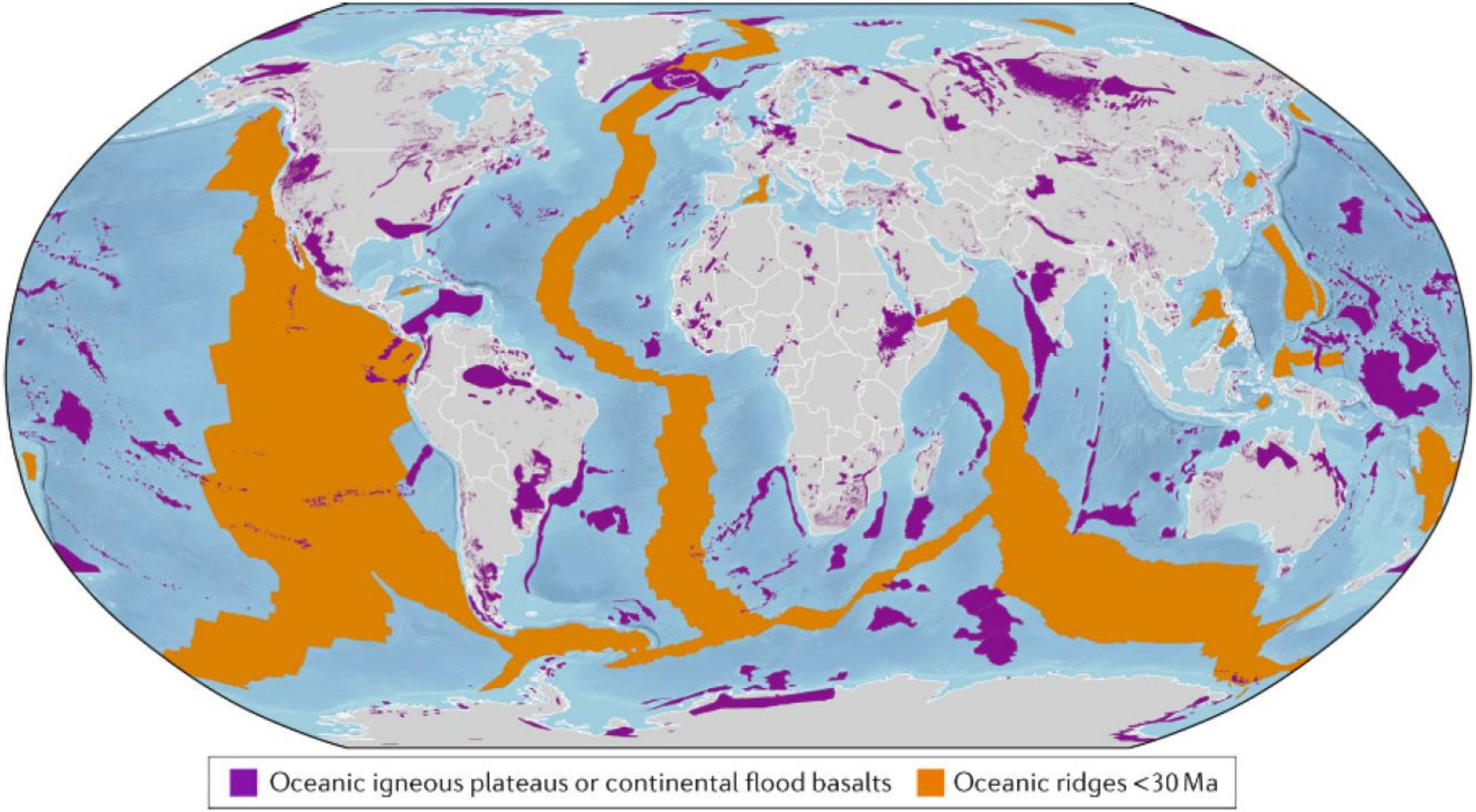
Basalts Turn Carbon into Stone for Permanent Storage: CarbFix*

Iceland's Hellisheiði Geothermal Power Station, is the third largest geothermal power station in the world and the site off ongoing mineral carbonation experiments.

Carbon dioxide dissolved in water reacted with the basalt (black) in this core to create carbonates (white), trapping the carbon in solid formed deep beneath the ground. Credit: Sandra Ó. Snæbjörnsdótttir

*Cartier, K. M. S. (2020), Basalts turn carbon into stone for permanent storage, *Eos,, 101,* https://doi.org/10.1029//2020 EO141721. Published on 20 March 2020.

Feasible Geological Formation Locations for *in situ* Mineral Carbonation



Basalts are relatively common throughout the world, including in the Northwestern U.S. and Hawaii; sub-ocean basalts may provide an even larger potential resource for mineralization. Oceanic ridges younger than 30 million years old are shown in orange, and oceanic igneous plateaus and continental flood basalts are shown in purple. Source: Snaebjornsdottir *et al*., 2020

GEOLOGICAL MINERALIZATION*

Alkali Earth Silicate + CO_2 → Alkali Earth Carbonate + SiO_2 + Heat

(*e.g.* Olivine/Basalt) **(Calcite a.k.a. Limestone)** **(Quartz)**

Specific Examples:**

Olivine: $Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$ -21.5kcal/mol

Serpentine: $Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$ -15.3kcal/mol

Wollastonite: $CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$ -21.5kcal/mol

*Seifritz, W. (1990). CO_2 disposal by means of silicates. *Nature* 345, 486. doi:10.1038/345486b0

**Others include Pyroxenes, Plagioclase, Anorthite, Brucite and Portlandite

TUESDAY, JULY 13, 2021

The Challenge: Critical Materials in Carbon Capture and Sequestration

Time (ET)	Session/Speaker	Topic/Comments
12:30 pm		Webex meeting session opens
12:55 pm	**Nancy Hicks**	Housekeeping for Virtual Workshop
1:00 pm	**James Zahler** Associate Director for Technology-to-Market, ARPA-E	Welcome and Introduction to ARPA-E
1:10 pm	**Doug Wicks** and **Joe King** Program Directors, ARPA-E	*Sequestering Carbon with Hybrid Employment of Mineral Assets* (Workshop motivation, goals, and operating parameters)
1:35 pm	**Roger Aines** Lawrence Livermore National Laboratory	*Mineralization and Engineering the Carbon Economy*
2:00 pm	**Todd Schaef** PNNL	*Carbon Sequestration in Basalts: Laboratory Studies and Field Demonstration*
2:25 pm	*Break*	
2:50 pm	**Breakout session**	**Technical approaches to *in situ* and *ex situ* CO_2 mineralization: Current Advantages and Disadvantages**
	Group A	**Chemical approaches**
	Group B	**Electrochemical approaches**
	Group C	**Microbiological approaches**
	Group D	**Phytomining approaches**
4:20 pm	**Break**	
4:30 pm	**Doug Wicks**	Reconvene. Preview/Homework for Day 2
4:35 pm	**Happy Hour**	

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